Validation of Material Models for Crash Simulation of Automotive Carbon Fiber Composite Structures (VMM)

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Co-Principal Investigators

US Automotive Materials Partnership LLC

DOE Annual Merit Review

June 7, 2017

Project ID: LM084

Project Overview

TIMELINE

- Project start date: 6/1/2012
- Project end date: 6/30/2017
- Percent complete: 100%

BUDGET

- Total project funding
  - DOE share: $3,445,119
  - Contractor share: $3,445,119
- Funding received in FY16 $1,001,103
- Funding for FY17:
  - DOE share: $534,459
  - Contractor share: $534,459

OBJECTIVES AT A GLANCE:

- **Evaluate Predictive Modeling Tools**
  - Validate carbon fiber composite material models for crash simulation, which will be demonstrated via design, analysis, fabrication, and crash testing.
- **Analyze Related Technological Gaps**
  - Correlate manufacturing, assembly, and evaluation processes to gaps in CAE characterization.

PARTNERS

- Northwestern University (sub-awardee)
- University of Michigan (sub-awardee)
- Wayne State University (sub-awardee)
- M-Tech International LLC
- ESI North America, Inc.
- Continental Structural Plastics
- Highwood Technology LLC
- Jesse Garant
- Dow Automotive
- Shape Corp
- ORNL-CFTF
- Chomarat
- Accutek
- BASF
- LSTC
- Altair Engineering
- AlphaSTAR Corp.
- **Project Lead: USAMP (GM, Ford, FCA Group)**

Relevance

VMM Objective: *Validation of Carbon Fiber Composite (CFC) Material Models for Crash Simulation of Automotive Structures*

Project Goal:

❑ Validate existing CFC material models in commercial crash codes and a selected number of models developed by previous Automotive Composites Consortium (ACC) projects with academic partners, which leveraged DOE funds.

❑ This will be accomplished by performing predictive crash simulations for critical high and low speed impact cases for a representative CFC Front Bumper and Crush Can (FBCC) System, then fabricating the FBCCs, conducting the appropriate crash tests, and comparing the results.

❑ The deliverable is a gap analysis of composite material models for crash simulations so that the analytical predictions can be more accurate in the future.
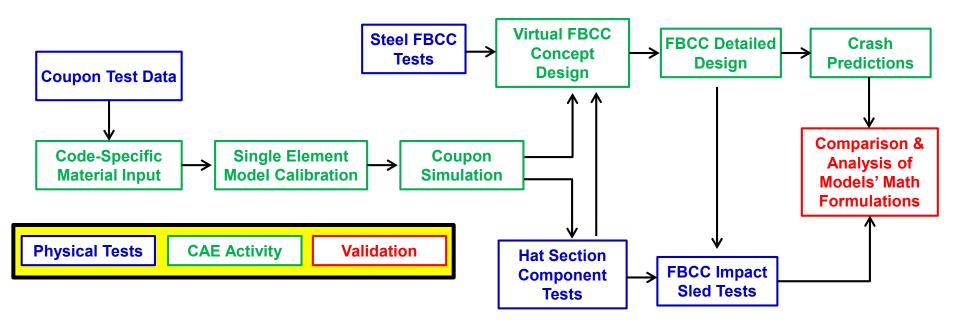
Relevance to DOE Vehicle Technologies Mission and DOE-VT MYPP:

❑ Accurate models will enable design of lightweight, crashworthy automotive structures with production-feasible carbon fiber composites for significant mass savings and improved fuel economy.

❑ Validation of these material models and the associated software packages through unbiased evaluation is necessary to evaluate their accuracy and ensure industry confidence in the predictions.

Approach and Outline of Tasks

Task 1: Project Administration and Management

Task 2: Characterization of Steel FBCC During Crash

Task 3: Design/Prediction of Composite FBCC Behavior

Task 4: Production of Composite FBCCs

Task 5: Crash Testing of Composite FBCCs

Task 6: Non-Destructive Evaluation

Task 7: Comparison of Experimental Results and CAE Predictions
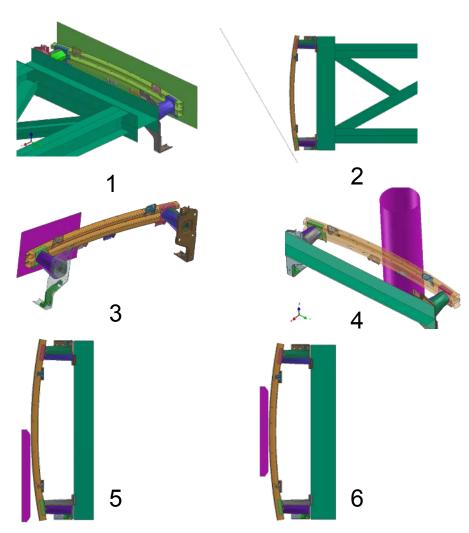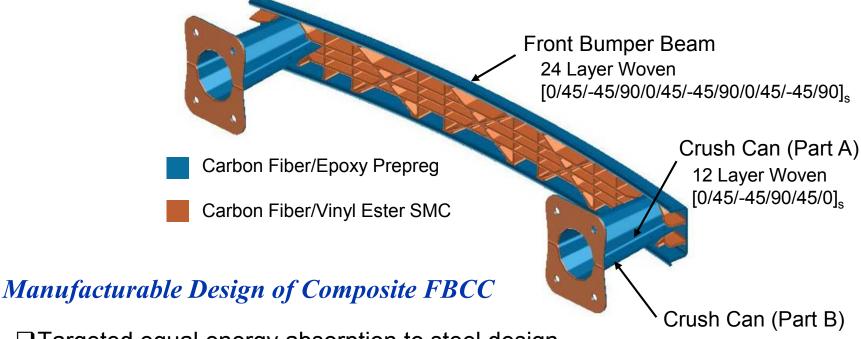
Technical Approach

☐ **Establish performance requirement based on crash testing of a production steel FBCC**

☐ **Design and build a composite FBCC, then crash test in six modes:**

1. 35 mph NCAP full frontal
2. 20 mph 30° Angular
3. 26 mph 40% Offset
4. 14 mph Center Pole
5. 9 mph quarter-point pendulum
6. 10 mph mid-point pendulum

☐ **Generate predictions:**

- Two Academic crash models
  - UM Meso-scale RUC model
  - NWU Micro-plane RUC model
- Five Commercial crash codes
  - PAM-CRASH
  - LS-DYNA
  - ABAQUS
  - RADIOSS
  - GENOA-MCQ

Technical Accomplishments and Progress

Front Bumper Beam
24 Layer Woven
$[0/45/-45/90/0/45/-45/90/0/45/-45/90]_s$

Crush Can (Part A)
12 Layer Woven
$[0/45/-45/90/45/0]_s$

Crush Can (Part B)

■ Carbon Fiber/Epoxy Prepreg

■ Carbon Fiber/Vinyl Ester SMC

Manufacturable Design of Composite FBCC

❑ Targeted equal energy absorption to steel design

❑ Targeted 30-35% reduced mass compared to steel design

❑ Composite FBCC components are compression molded

- Prepreg forms primary structure

- SMC forms complex geometries and enhances tailorability

❑ The five components are joined adhesively

- Rivets enhance the bond between the crush can halves

Manufacture of Composite FBCCs

1. Cut and Kit the Materials
   - CF prepreg and SMC

2. Preform the Prepreg
   - Form the prepreg to shape

3. Mold the Components
   - SMC+prepreg co-compression molded

4. Trim the Components
   - Components CNC milled to shape

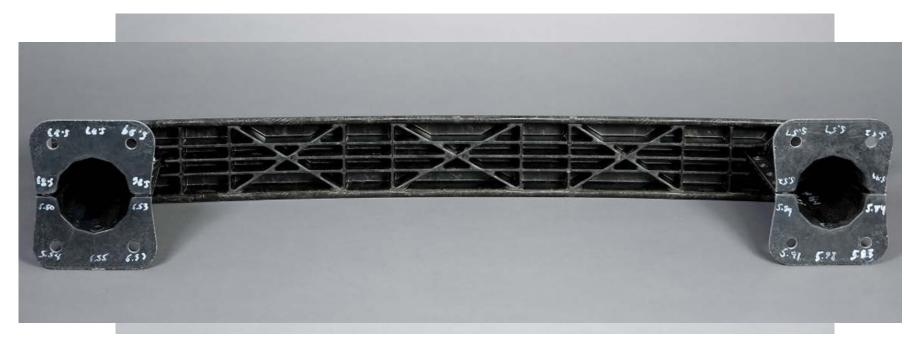5. Assemble the Components
   - Joined with adhesive and rivets
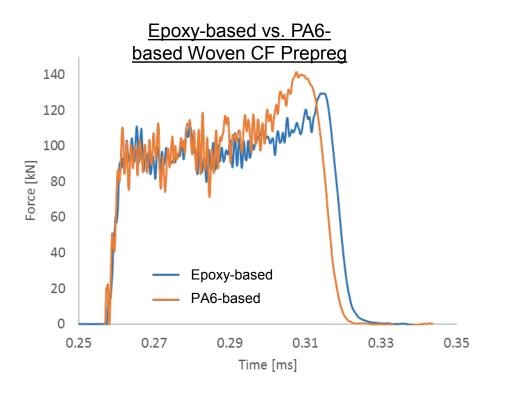
Assembled FBCC Ready for Testing

Alternative Materials Explored

- ❑ Base material: Epoxy / woven carbon fiber prepreg (Thermoset resin)
- ❑ Alternative materials examined:
  - ❑ PA6 / woven carbon fiber prepreg tape from BASF (Thermoplastic resin)
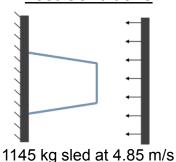 - ❑ PA6 / non-crimp fabric (NCF) processed using ORNL's "Low Cost Carbon Fiber" (LCCF)

Epoxy-based vs. PA6-based Woven CF Prepreg

Pre-test Setup

Test Conditions

1145 kg sled at 4.85 m/s

Epoxy-based Post-Test

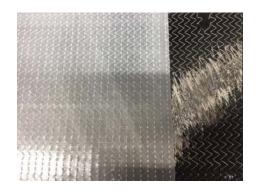### PA6-based Post-Test

Manufacture of PA6 / LCCF Panels

- ❑ Examined an innovative approach to manufacturing with the ORNL LCCF
  - ❑ The LCCF was formed into a NCF with PA6 film between each layer
  - ❑ The sheets were then consolidated to impregnate the fabric with PA6
- ❑ Results were promising, but more work is needed to perfect the manufacturing procedure and eliminate defects
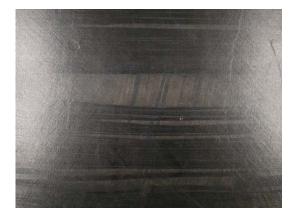
LCCF NCF

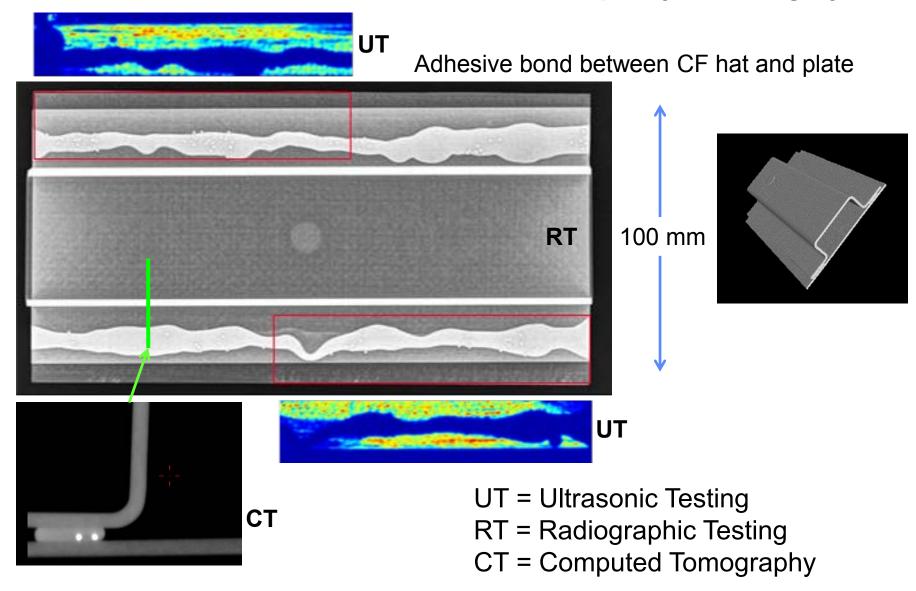Film Stitched into NCF

Consolidated Panel

- Consolidated panels showed "fiber wash" due to melting of stitching thread

Comparison of NDE Methods

Evaluated a suite of NDE methods for FBCC quality and integrity

UT

Adhesive bond between CF hat and plate

RT

100 mm

UT

CT

UT = Ultrasonic Testing
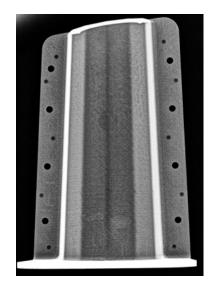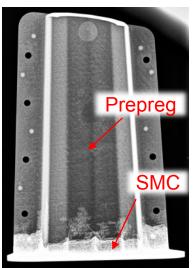RT = Radiographic Testing
CT = Computed Tomography

NDE of Crush Cans

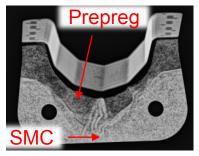Low-energy radiographs (side view and end view) of crush can.

a) **"Good" CC** with low dart location and low intrusion of SMC

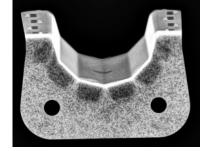b) **"Discrepant" CC** with high dart location and significant intrusion of SMC

Side View

End View

a) Good CC   b) Discrepant CC

No delaminations, voids, or foreign matter found in the CC components

Crush Can Material Performance

Results of Tensile & Compression Coupon Testing

Compression Coupons

- CAE material cards were based on flat plaque data

Crush Can Half Ready to Cut

- Crush cans were cut into coupons to compare their performance to the flat plaques
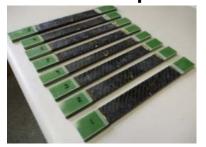
Coupons sampled from 6 crush can halves

Tensile Coupons

- **Significant reductions** in properties were measured in crush can coupon tests
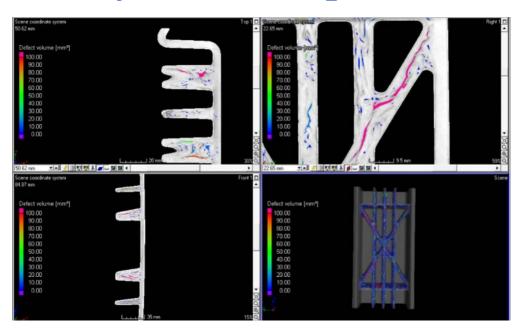
Comparison of Flat Plaques and Crush Cans

Test	Modulus (GPa)	Failure Stress (MPa)
Compression Testing		
Flat Plaque	38.5 ± 0.2	446 ± 27
Crush Can Coupons	32.9 ± 2.8 (-14.5%)	352 ± 44 (-21.1%)
Tensile Testing		
Flat Plaque	37.4 ± 0.2	486 ± 20
Crush Can Coupons	37.0 ± 5.8 (-1.1%)	364 ± 86 (-25.1%)

- Attributed to fiber bunching, spreading, and wrinkling

NDE of Front Bumper Ribs
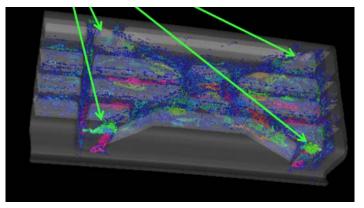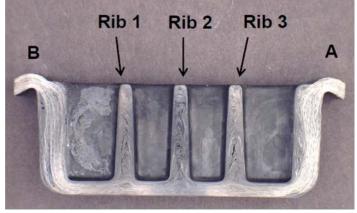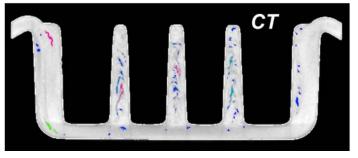
CT porosity analysis of FB section showing perspective views and orthogonal slices.

The color of the porosity indicates the volume of the pore/crack.

Porosity and delaminations were detected
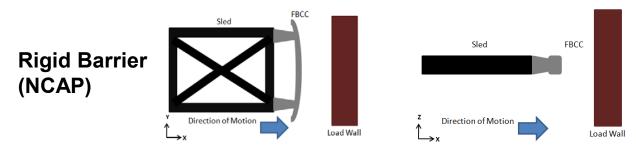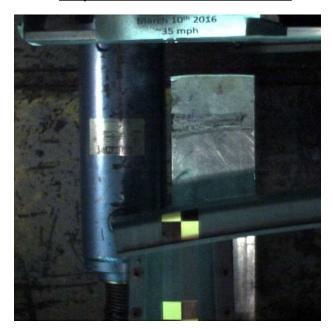
Comparison of Experiment vs Predictions
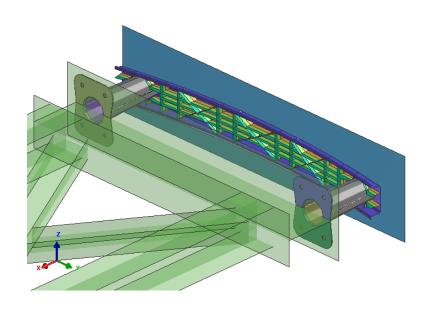
❑ Predictions were collected from 5 commercially available codes and compared to experimental results in each of the 6 crash modes

Rigid Barrier (NCAP)

Representative Crash Video
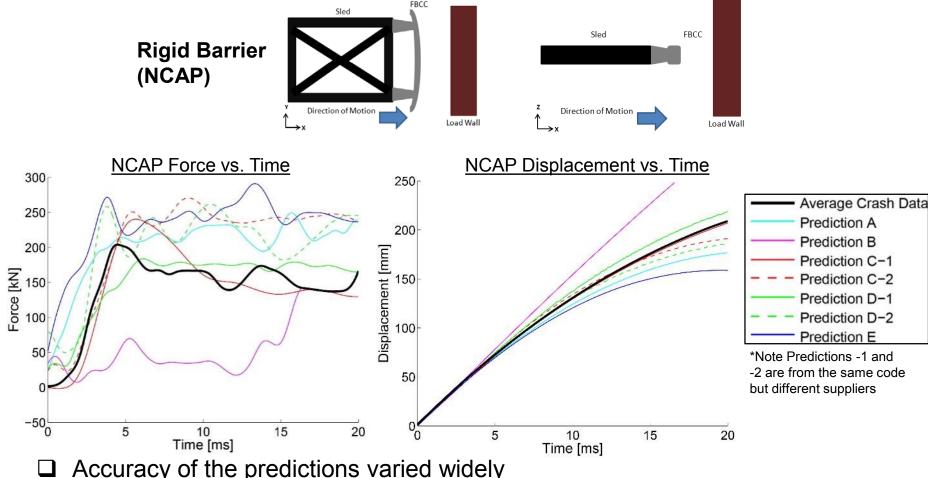
Representative Simulation Animation

Comparison of Experiment vs Predictions

❑ Predictions in 5 commercially available codes were compared to experimental results in each of the 6 crash modes

Rigid Barrier (NCAP)

NCAP Force vs. Time

NCAP Displacement vs. Time

	Average Crash Data
	Prediction A
	Prediction B
	Prediction C-1
	Prediction C-2
	Prediction D-1
	Prediction D-2
	Prediction E

*Note Predictions -1 and -2 are from the same code but different suppliers

❑ Accuracy of the predictions varied widely
❑ Most predictions over-estimated crash performance in NCAP
   ❑ However, NDE identified defects not accounted for in CAE

Objective Comparison via CORA
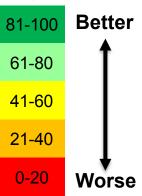
Crash Mode	Software A	Software B	Software C		Software D		Software E	Average
			Supplier 1	Supplier 2	Supplier 1	Supplier 2		
NCAP	62	35	86	49	80	60	37	58
IIHS	67	6	83	55	65	26	46	50
Angular	31	7	30	57	61	29	35	36
Pole	37	58	70	66	42	5	31	44
LS Center	34	55	35	70	40	31	38	43
LS Quarter	65	7	75	73	78	38	64	57
Average	49	28	63	61	61	31	42	

Objective comparison using CORA: "Correlation and Analysis" [1]
- ❑ Assigns score based on accuracy of amplitude, phase, and slope

Key Observations:
- ❑ Overall, CAE was not reliable in accurately predicting the experiment
- ❑ Accuracy of the predictions varied with:
  - ❑ Software package
  - ❑ Supplier
  - ❑ Crash mode

81-100	**Better**
61-80	
41-60	
21-40	
0-20	**Worse**

[1] C. Gehre, H. Gades, and P. Wenicke, "Objective Rating Of Signals Using Test And Simulation Responses", . Proc. Int. Tech. Conf. Enhanced Safety Vehicles, 2009.

Technological Gap Analysis

Material Characterization

- Improve material test property accuracy and correlation to full structure
- Refine material models for improved treatment of elements post-yield under brittle failure
- Develop improved treatment of finite elements under delamination
- *Implement in-situ characterization of composite properties due to draping, forming, & curing (ICME)*

Design

- Consider effects of geometry decisions on post-forming fiber orientation
- Develop improved methods for integration with vehicle body structure specific to composites
- *Reduce time to integrate manufacturing effects into virtual design assessment (ICME)*

Joining

- Improve experimental characterization of composite-composite joints and development of adhesive models
- Develop faster + stronger methods for component joining

Material Selection

- Enhance availability of low-cost carbon fiber material production sources
- Consider elongation properties for reduced damage generation during low energy events

Non-Destructive Evaluation

- Improve ability to measure fabric waviness and stretch in thick composite panels
- Develop better methods for areas with tight radii

Manufacturing

- Improve consistency of fiber-resin architecture throughout the part
- *Utilize modeling of draping, flow, and curing analysis to reduce defects in early parts and link predictions to structural analysis (ICME)*

Responses to Previous Year Reviewers' Comments

Thanks for valuable feedback - A few comments can be addressed:

Question 1: Reviewer 5 asked about Approach.

Predictions for FBCC performance assumed perfect bonding in most cases due to the challenges associated with modeling the adhesive. As a result, crash modes that put significant stress on the joints (i.e. angular, pole, and LS-center) failed at significantly lower loads than the CAE models predicted. Improved methods for implementing accurate adhesive models is an area recommended for future investigation.

Question 2: Reviewer 2 asked about Technical Accomplishments.

The effects of manufacturing variance in the thermoset composite FBCC components is an important contributor to CAE inaccuracies, due to the interaction of multiple factors such as fiber orientation changes, SMC material mismatches, molding process and cure instabilities, adhesive cure variance, etc, which were not accounted for in the CAE models.

Question 4. Reviewer 3 asked about Future Research.

The integration of predictive manufacturing simulations and use of NDE methods for calibrating predictive analysis for effects of material failure and manufacturing variance are areas for further research.

Collaboration and Coordination with other Institutions

❑ **Northwestern University**

- Sub-recipient. Completed 2015

❑ **University of Michigan**

- Sub-recipient. Completed 2015

❑ **Wayne State University**

- Sub-recipient. Completed 2016

❑ **M-Tech International, LLC**

- M-Tech is Technical Project Manager.

❑ **ESI**

- ESI is the primary design/CAE vendor for commercial modeling codes.

❑ **Continental Structural Plastics**

- CSP was the major composite fabrication supplier.

❑ **Century Tool & Gage**

- Century produced the compression molding tools for FBCC components.

Collaboration and Coordination (Cont.)

❏ Highwood Technology LLC

- Highwood Technologies was responsible for the development of NDE.

❏ Dow Automotive

- Dow was responsible for joining and final assembly of the composite FBCC.

❏ Shape Corp

- Shape led the evaluation of Thermoplastic materials for FBCCs.

❏ Chomarat North America Inc

- Chomarat processes ORNL-LCCF into formable Non-Crimp Fabric.

❏ Livermore Software Technology Corp

- LSTC calibrated LS-DYNA models with VMM material data to deliver custom material cards and CAE predictions for the FBCC.

❏ Altair Engineering

- Altair calibrated RADIOSS models with VMM material data to deliver custom material cards and CAE predictions for the FBCC.

❏ AlphaSTAR Corp.

- AlphaSTAR calibrated GENOA-based multi-scale models with VMM material data to deliver CAE predictions for the FBCC.

This project will complete in June 2017 and no further efforts are planned.

Project Summary

Accomplishments:

- A composite FBCC was successfully designed, built, and tested.

- NDE tools were evaluated and utilized to identify defects in the FBCC.

- Test results were compared to predictions of the performance in six crash modes by various suppliers in several software packages.

Conclusions:

- CAE predictions of carbon fiber composite crash performance are not universally accurate. Accuracy varied by software package, supplier, and crash mode.

- Many technological gaps exist that erode the accuracy of the CAE predictions. These gaps relate both to the software and material models themselves, as well as our ability to design, manufacture, test, and non-destructively evaluate a carbon fiber composite structure.

- Integrated computational materials engineering (ICME) techniques may greatly improve accuracy by predicting material property variations that result from manufacturing imperfections.

Acknowledgements

Dr. Felix Wu (DOE-VTO), Dr. Carol Schutte (DOE-VTO) and Aaron Yocum (NETL)

Technical Backup Slides

Materials Selected

❑ **Composite material systems selected:**

- Carbon-fiber/epoxy prepreg
  - 2x2 twill woven fabric
  - Cytec MTM® 54FRB resin
- Carbon fiber SMC
  - 25.4 mm carbon fiber length
  - CSP CVS-1016-2BK resin (epoxy acrylate)
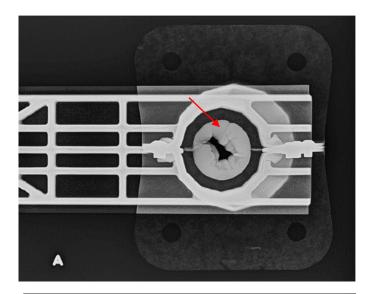- Glass fiber SMC (used only in crush can flange)
  - CSP 834 SMC

❑ **Adhesive bonding selected as primary joining technique:**
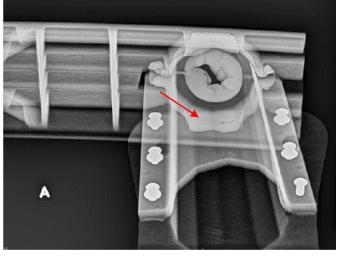
- Dow Automotive Betaforce 2850 2-part urethane
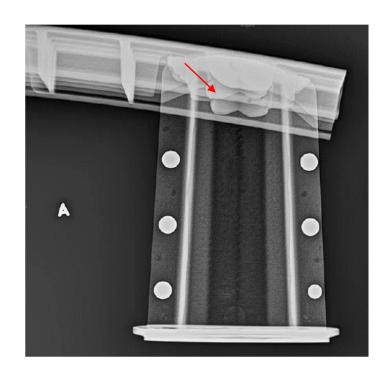- Reinforced with "peel stopper" rivets or bolts

Assembly Inspection
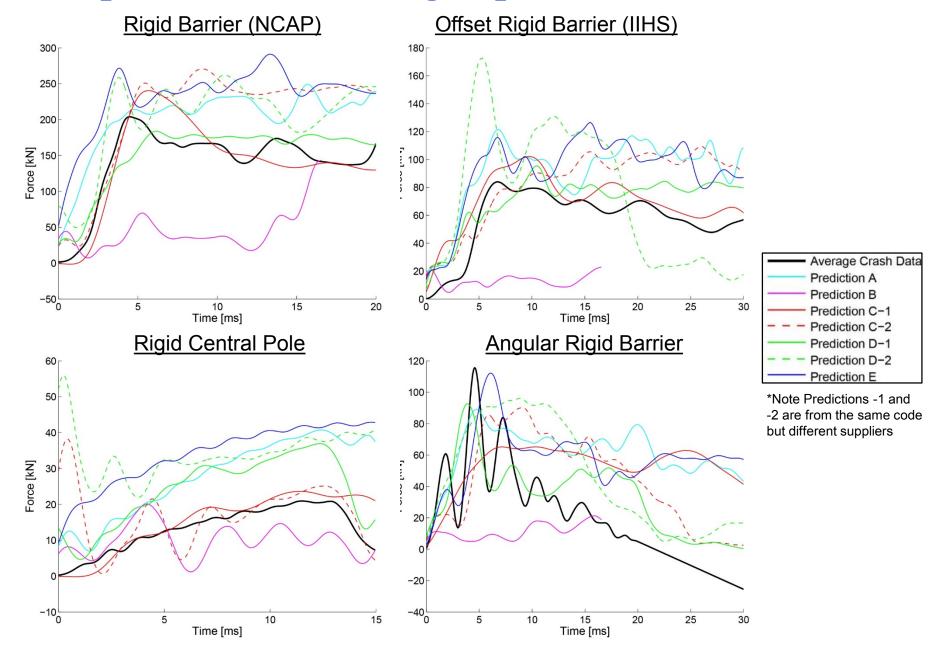
Inspections confirmed that adhesive application was liberal and filled the interfaces intended

Comparison Results: High Speed Modes

Rigid Barrier (NCAP)

Offset Rigid Barrier (IIHS)

Rigid Central Pole

Angular Rigid Barrier

Legend:
- Average Crash Data
- Prediction A
- Prediction B
- Prediction C-1
- Prediction C-2
- Prediction D-1
- Prediction D-2
- Prediction E

*Note Predictions -1 and -2 are from the same code but different suppliers

Comparison Results: Low Speed Modes

USAMP

Low Speed Center Point

Low Speed Quarter Point

Legend:
- Average Crash Data
- Prediction A
- Prediction B
- Prediction C-1
- Prediction C-2
- Prediction D-1
- Prediction D-2
- Prediction E

*Note Predictions -1 and -2 are from the same code but different suppliers